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CHARACTERIZING SHRAPNEL AND DEBRIS PRODUCED IN HIGH POWER LASER EXPERIMENTS

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ABSTRACT

As large laser facilities increase in beam energy and target size, the propensity to produce shrapnel and debris that may impact target-facing optics lifetimes also increases. We present techniques and results using silica aerogel and thin glass plates to characterize the number, velocity, size, and spatial distribution of shrapnel and mass distribution of debris. We have conducted experiments on the HELEN laser to develop these techniques and provide data to support computer modeling of shrapnel and debris generation. We have begun to measure shrapnel and debris generation on Omega and are evolving plans to make similar measurements on NIF. These techniques appear viable for measuring shrapnel and debris with sufficient resolution to quantify their asymmetric deposition within the target chamber. These passive measurements can confirm improved target designs that reduce target shrapnel and debris effects and therefore aid in extending optics lifetime. Ultimately, these data support the most efficient use of optics in executing experimental campaigns on large laser facilities.

I. INTRODUCTION

The target-facing optics of large lasers are exposed to target emissions, notably shrapnel and debris. These can be debris shields protecting the final optics, or disposable debris shields protecting the debris shields, extending their lifetime. Target-facing optics are affected by shrapnel and debris production. Characterizing shrapnel and debris can assist in the approval process of experiments, aid in estimating optics use, and contribute to efficient operations scheduling of optics maintenance and ‘optimal’ shot sequence. This data can also contribute to improving computer modeling of shrapnel and debris generation.

For these reasons, we are developing in-chamber diagnostic capabilities to measure in-situ shrapnel and debris from experiments. The shrapnel data most useful from such a diagnostic capability are the spatial distribution of the shrapnel, its number/size distribution, and its velocity. This information, combined with established impact damage algorithms for optical materials, would allow accurate predictions of optic lifetime and ultimately confirm the success of shrapnel generation mitigation strategies, for example, employing new types of materials in targets such as high-Z doped plastics.

We present a technique using silica aerogels to characterize the number, velocity, size and spatial distribution of shrapnel. We investigated the use of aerogel as a shrapnel diagnostic by creating shrapnel in a series of experiments on the HELEN laser at AWE and capturing the shrapnel in pre-positioned aerogel-filled holders placed 10 to 20 cm behind metal foil targets. The foils were irradiated by 1 to 4 ns, 0.5- or 1-mm spot size, 2ω pulses. Beam energies ranged from <100 to 400 J. Targets were either 1-mm diameter disks or 5-mm square plates, typically 250 microns thick, made from Ta, carbon steel, or Al. Figure 1 shows a typical aerogel, density ~20 mg/cc, with embedded shrapnel produced by this technique.

II. DISCUSSION OF SHRAPNEL AND DEBRIS DIAGNOSTIC REQUIREMENTS

We require this diagnostic to measure the number, direction, size, and velocity of shrapnel generated in a target experiment. While the accuracy necessary for each measurement has not yet been determined, if size is known to within ± 25 μm and velocity to within ± 30%, reasonable predictions of impact to target-facing optics should be possible. These criteria should also be sufficient to support evaluating the ability of existing modeling capabilities to predict and understand the observed data. Techniques to measure debris (condensed material) deposits, such as Inductively Coupled Plasma – Mass Spectroscopy or even X-Ray Flourescence, can detect nano-gram quantities or few Å thicknesses and should be acceptable resolution to quantify debris deposition.

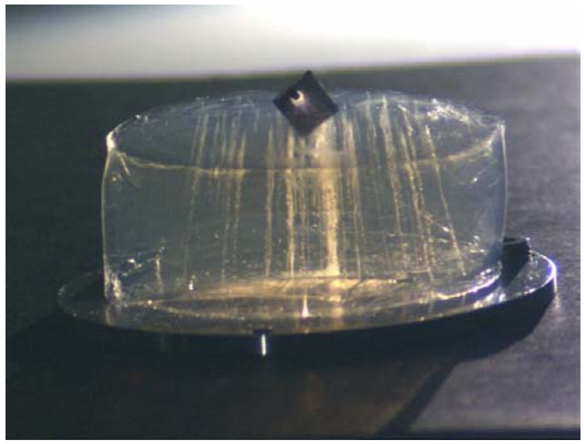

Fig 1. A laser target and its associated shrapnel were captured in aerogel.

III. CONCEPT OF USING AEROGEL TO DIAGNOSE SHRAPNEL

To try to meet this set of requirements for measuring shrapnel, we examined the use of low density silica aerogel to produce a 'record' of the shrapnel particles. The concept is to place the aerogel close enough to the target (10 – 20 cm) to trap a significant fraction of the shrapnel produced by a particular target. Aluminum cups holding aerogel could routinely be placed inside laser facility chambers using diagnostic instrument manipulators in use with target diagnostics to get close-in access to characterize the shrapnel output of a target.

Once removed from the chamber, x-rays (e.g. synchrotron) could be used (and have been used) to produce radiographs of the shrapnel-laden aerogel, at multiple angles, so as to account for irregular shrapnel shapes. The x-rays can also be used, if needed, to determine each particle's atomic number (and hence its density). The resulting data would include the size and position of all shrapnel embedded in the aerogel by atomic number.

IV. DETERMINATION OF SHRAPNEL VELOCITY

Since we can measure the shrapnel particle's size, penetration depth, and atomic number using radiography, the initial velocity may be calculated using a model that relates the penetration depth to the incident velocity for a given aerogel density. Our initial approach was to create a simple model relating incident particle size to its depth in the aerogel. We plan to continue to evaluate this model, both with further particle impact studies on aerogel and continued comparison with modeling. We will improve the model over time to meet our established need for accuracy in our damage studies.

The approach is a simplification of the analysis of penetration physics reported by Anderson and Ahrens [1]. Since shrapnel particles of interest have minimum diameters of at least several microns, the aerogel will appear to the shrapnel particles as a low-density continuum due to the very small aerogel pore size (~10-100 nm.) For shrapnel, we consider a simplified approach to that noted above by using a "snowplow model" for the drag [1]. This results in the following expression of the ratio of penetration depth to particle size [2]:

$$x(pen)/d_p = -(1/\alpha)\ln[(P_c/D\rho_o)^{1/2}/u_o],$$

where x(pen) is the depth of penetration, d_p is the shrapnel particle diameter, D is the drag coefficient, ρ_o is the initial density of the aerogel, P_c is the compaction strength of the aerogel, u_o is the initial particle velocity, and α is $(D\rho_o/\rho_p)$ where ρ_p is the density of the shrapnel particle. Eq. (1) applies to cases where the particle does not suffer significant ablation or compressive failure from plastic flow or fracture, which is ~ 2.5 km/s for Ta, the main shrapnel material studied thus far. We fix the drag coefficient as 0.75. The compaction strength used is 10% of the compressive modulus at this density. [3]. Analyses during x-ray radiography of the edges of many of the tracks did not reveal ablated Ta in a representative aerogel sample and this value for P_c keeps the majority of particles with velocities below 2.5 km/sec. More experiments remain to be done to calibrate the aerogel and settle on a value for P_c. Low velocity (<300 m/s) and large particle (250 micron diameter) calibration experiments showed too much spread in the data to converge on a value.

V. EXTRACTING THE AEROGEL SHRAPNEL DATA

Synchrotron radiation on a beamline of the Stanford Linear Accelerator was used to produce radiographs at three angles (0°, 120°, 240°) for a dozen of the shrapnel-laden aerogels produced in the HELEN experiments. This capability allowed the resolving of particle diameters down to ~ 7 microns. Reconstruction of the data required 'tiling' of up to 63 individual radiographs since the beam cross section was substantially smaller than the sample. Particles were required to have three intersections, one at each angle, to confirm a particle was positively located at a particular site. We computed each particles' depth from the top of the aerogel, taken as the depth of penetration, and determined each particle's size from the recorded pixels. This shot involved using a single ~384 J, 1 ns, 527-nm wavelength, 960-micron diameter laser beam to shock a single 1-mm diameter, 250 micron-thick Ta disk. The aerogel was placed 12 cm away. The total capture of shrapnel accelerated from the back of the disk by the aerogel allowed estimating of the angle of dispersion at this stand-off as 22° (full angle). When we apply equation 1 to the data reduced from the radiography, we create the particle size -- velocity plot shown in Figure 2. There are 857 particles accounting for 11% of the original Ta disk mass. The largest shrapnel fragment is 112 microns and is estimated to have been traveling 200 m/s when it impacted the aerogel.

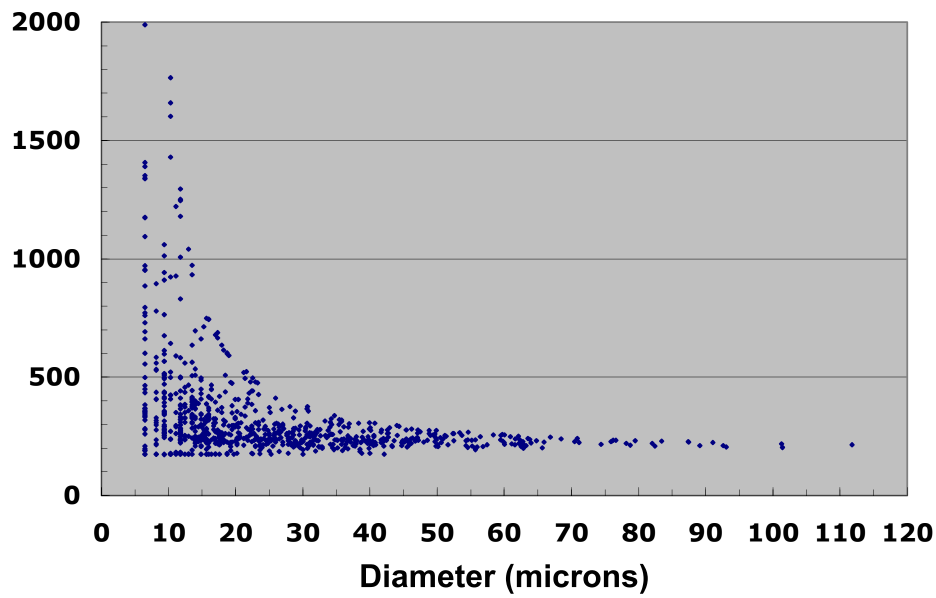

Fig 2. The size – velocity profile predicted using the 'snow plow' model.

VI. COMPLEMENTARY DATA FROM BOROFLOAT WITNESS PLATES

While the data from aerogels provides a complete set of shrapnel information (number, size, velocity, direction), the individual aerogels are more expensive than borofloat witness plates of similar area. We wanted to determine whether borofloat witness plates might be used subsequent to aerogel characterization of a type of experiment to monitor that the recurring shrapnel and/or debris continued to exhibit the features revealed by aerogel testing. This would both simplify and reduce the cost of shrapnel and debris monitoring. We compared the surface damage to a borofloat plate exposed to approximately the same shrapnel environment as an aerogel sample. The shrapnel spectrum (size/velocity data) established by aerogel analysis as described above was then used to estimate the number and size distribution of individual damage sites that would be produced on the borofloat witness plate. This was done using the empirically-based dimensionless scaling developed by Tokheim [4] that relates velocity (v), impactor density (ρ) and diameter (L), and target material yield strength (Y) to damage region diameter (D_s) in the following equation, where we take Y to be 250 MPa:

$$D_s/L = \beta[\alpha\rho v^2/Y]^{1/3}, \text{ where } \alpha = \min(0.1\bullet\rho v^2/Y, 1) \qquad (2)$$

The glass plate was scanned using a Nikon NEXIV microscope. This microscope can scan a 10-cm square glass plate with a pixel size of 4 μm in less than one hour, producing output files that include each damage area location, size, and an image of the damage site. A comparison of the NEXIV data from the borofloat plate and the estimate of craters expected using the aerogel shows excellent agreement for diameters above 100 microns and suggests that borofloat witness plates may be useful for this shrapnel monitoring purpose and as a check on the aerogel results. The scan produced more than 8000 sites below 100 microns in diameter that is a combination of smaller shrapnel and debris sites.

VII. USE OF VISAR OPTIC TO ASSESS SHRAPNEL DAMAGE

Recent hydrodynamic experiments on the Omega laser that used diamond anvil targets produced sufficient shrapnel to damage the VISAR final optic. The 5-cm diameter optics were collected from four of the experiments, cleaned, and then scanned on the NEXIV microscope to measure the total damage for each. The total laser energy for each experiment ranged from 64 J to 950 J in pulses from 1 to 3.7 ns. The number of damage sites ranged from several hundred to more than 9000 for the highest energy shot. The total area of damage per optic ranged from 0.1 (64 J) to 10 mm^3 (950 J). Empirically-based scaling specific to a particular target type will be very useful for predicting/assessing possible target induced damage. Diagnostics employing target-facing optics should be considered to aid in similar data collection.

VIII. CONCLUSION

We have examined the use of low density silica aerogel, combined with radiography, to assess the shrapnel size and number generated by targets in large laser facilities. We have evolved a simplified model that provides an estimate of shrapnel velocities. We have shown that glass witness plates can be used to complement the aerogel data using the Nikon NEXIV microscope system to rapidly scan surface damage and debris sites. We conclude that these techniques may be viable for measuring shrapnel with sufficient resolution to quantify their asymmetric deposition and subsequent effects to target-facing optics. Diagnostics that employ an optic as the final component (e.g. VISAR) can contribute to shrapnel and debris characterization. Both techniques have been fielded on Omega and Helen and plans are evolving for implementation on NIF.

IV ACKNOWLEDGMENTS

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